Colour-coded echographic flow imaging and spectral analysis of cerebrospinal fluid (CSF)*

Part III. In-vitro study of low flow velocity detection related to decreasing particle concentration (hematocrit) and tube lumen

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Received: 8 November 1991; accepted: 8 January 1992

Abstract. An in-vitro steady flow system was designed to determine the lowest flow velocities that can be detected by echographic colour flow imaging and spectral analysis. The flow detection level was determined hydrostatically by reducing the fluid level to below the point at which a flow signal was visible, then increasing the height until the colour flow reappeared. This was confirmed in all instances by spectral analysis. The height (angle-corrected velocity) of the spectral envelope was also determined. Mean volume flow was then obtained by using a graduated cylinder and a stop watch. The lowest hematocrit detectable was identified using a stepwise dilution of packed human red blood cells with 0.9% sodium chloride. Three different PVC-tubes with inner diameters of 2.1 mm, 1.1 mm and 0.51 mm were used. It was found that: 1) echographic flow imaging is remarkably sensitive to low concentrations of scattering particles (lowest hematocrit detected by colour flow and spectrum was 0.003% using the 2.1 mm diameter tube); 2) lowest hematocrit values which allowed detection of true mean flow velocities below 2 cm/sec increased with decreasing lumen: 0.006% for the 2.1 mm tube; 0.22% for the 1.1 mm tube and 1.6% for the 0.51 mm tube; 3) higher velocities and/or greater lumina were necessary to detect hematocrit values below 1%; 4) for a hematocrit between 0.1% and 44% measured mean flow velocities were less than half the values obtained from spectral envelope; 5) the error of spectral flow velocity determination was relatively constant for this hematocrit range (0.1% - 44%), but varied with tube size; 6) minimal concentrations of red blood cells could be differentiated from air bubbles by signal intensity at constant receiver gain settings; 7) there was no difference in the height of the velocity envelope between air and red blood cells. The diagnostic, clinical and scientific implications of these findings are discussed.

In magnetic resonance imaging (MRI) signal variations due to moving protons are used to detect CSF-flow [1], whilst MRI, echographic flow imaging needs an appropriate concentration of moving reflectors within the fluid or strong fluid-fluid interfaces. For these reasons it might be considered to be unsuited for the detection of CSF-flow. When echographic flow imaging was, however, first observed, it seemed of great interest to establish, 1) whether colour flow imaging was sufficiently sensitive to detect a relatively low particle density as compared to blood; 2) which was the lower limit of particle concentration; 3) if, or to what degree flow detection depended on vessel or tube lumen. These questions led us to design an experimental setting that could enable investigation of flow velocity as related to particle density (hematocrit) and cross-sectional area of the fluid-containing canal (tube).

Material and methods

An in vitro steady flow system was set up using hydrostatic pressure and human packed red blood cells diluted with 0.9% sodium chloride solution (Fig. 1). Plastic tubes (PVC) with specified inner diameters of 2.1 mm, 1.1 mm and 0.51 mm were used. The diameter was additionally verified over 20 cm tube length by filling the tubes with high density Barium and using an appropriate high resolution X-ray system and optical enlargement. The tubes were then cleaned, immersed in water and studied at an angle of between 54° and 60° with the transducer attached to a stable clamp. The mean distance of the tube from transducer surface was 7.5 cm corresponding to the sample volume depth. Sample volume size was 4 mm or 5 mm. Colour flow imaging and spectral analysis were performed using a commercial scanner (Acuson 128, Acuson Corp., Mountain View, CA 94043, USA). Doppler frequency used for all measurements was 3.5 MHz (phased array sector). Output power was set to "LOW". The lowest possible colour flow which could be clearly identified was determined by one observer as the other increased hydrostatic pressure from different levels below the detection threshold. Spectral confirmation of observed colour flow and readings of time averaged maximum velocity \( v_{\text{max}} \) (average of spectral envelope) were obtained in each instance (Fig. 3 d). Actual volume flow \( v_{\text{vol}} \) was determined by an appropriate measuring cylinder and a stop-watch. The true mean flow velocity \( v_{\text{mean}} \) was then calculated and together with \( 2v_{\text{max}} \) compared with the recorded velocities \( v_{\text{max}} \). Receiver gain was optimized for the first in vitro study and then adjusted to this level in the entire experimental series. At the end of each set of readings of the

* Presented at the IPR meeting in Stockholm, May 1991. Selected for publication by an International Group of the ESPR.
Correlation of mean velocities \( v_{\text{mean}} \) (as calculated from measured volume flow and tube diameter), \( 2v_{\text{mean}} \) and spectral envelope \( v_{\text{tam}} \) with hematocrit and three tube diameters (0.51 mm, 1.1 mm, 2.1 mm) are shown in Fig. 2. It can be seen that: 1) Lowest mean flow velocities \( v_{\text{mean}} \) detected by colour flow imaging (with spectral confirmation in all instances) were 0.5 cm/sec (2.1 mm), 1.0 cm/s (1.1 mm) and 1.3 cm/sec (0.51 mm). 2) Detection threshold of flow increased with decreasing hematocrit when values were below 0.1%, 1% or 10% for a tube lumen of 2.1 mm, 1.1 mm and 0.51 mm respectively. 3) Lowest hematocrit values where colour flow was still identified were 0.003% (2.1 mm), 0.03% (1.1 mm), 0.05% (0.51 mm). 4) With a hematocrit of 40% spectral readings \( v_{\text{tam}} \) were above the flow velocity calculated from measured volume flow \( 2v_{\text{mean}} \) by a factor of 2.9 (2.1 mm), 1.3 (1.1 mm) and 1.6 (0.51 mm). \( v_{\text{tam}} \) did however approach \( 2v_{\text{mean}} \) at flow velocities in the order of 5-7 cm/sec for all three tube diameters. 5) The error of spectral flow velocity determination was relatively constant for a certain hematocrit range (0.1%-44%), but varied with tube size.

Even borderline concentrations of red blood cells could be distinguished from air inclusions by signal intensity with a constant receiver gain setting, but no significant difference of velocity envelope between air and red blood cells was noted.

**Fig. 2a-d.** Detection of low flow velocities related to hematocrit and tube lumen. Each symbol is the mean of 10 readings.

**a** Sensitivity to low flow velocities is significantly larger with the 2.1 mm inner diameter as opposed to 1.1 or 0.51 mm.

**b-d.** The readings from spectral envelope are substantially higher than either \( v_{\text{mean}} \) or \( 2v_{\text{mean}} \) and vary in proportion to \( v_{\text{mean}} \) with tube lumen, questioning the value of velocity readings in this range. Indicated velocities are, on the other hand, surprisingly constant over a wide range of hematocrit values. Increasing standard deviation of readings with decreasing hematocrit was due to larger fluctuations of readings.